REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-02-

0349

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE 5/28/02

3. REPORT TYPE AND DATES COVERED Final Technical Report

4. TITLE AND SUBTITLE
Unconventional laser guide stars and wavefront correction of blue starlight

5. FUNDING NUMBERS
F49620-~~98-0374~~
98-1-0374

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 Words)***

In this project we established by theory and experiment 1) that a ¼ Joule, 20 ns, ultraviolet laser pulse could create (near 20 km altitude) a return signal to the transmitting telescope that would appear, for 20 ns, to have a brightness temperature of millions of degrees, and thus serve as a guide star for high-order corrections of blue starlight, 2) that a much lower energy (~one hundred microjoules) femtosecond laser pulse could create an upward-traveling pulse near the tropopause with its wavelength shifted from the driving pulse, 3) that exact, finite-energy, pulse solutions of Maxwell's equations can have an electric (or magnetic) field with zero y-component everywhere in space, 4) that Maxwell's equations place no limit on the smallness of extinction experienced by a focused pulse of finite energy passing through finite crossed polarizers, and 5) that wavefront correctors based on photo-refractive spatial-light-modulators are unlikely to have their speed-of-response improved.

14. SUBJECT TERMS
laser guide stars, adaptive optics, atmospheric radiation, stimulated Raman scattering, femtosecond pulses in air, Maxwell pulses, spatial light modulators

15. NUMBER OF PAGES 10

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified		unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

1122 126

1. Introduction and Project Objective

The sharpness and sensitivity with which the best telescopes can view the stars is limited by the distortions in the stars' images caused by atmospheric turbulence. Over the past several decades, astronomers have learned to remove some of the effects of atmospheric turbulence by clever manipulation of deformable mirrors, that is, by "adaptive optics," or AO. This manipulation is made on the basis of an image that is known to come from a single bright point-like source, called a "guide star." Since real stars that are bright enough to serve as a guide star do not appear in all portions of the sky, lasers have been employed to create artificial "laser" guide stars (LGS). The laser can excite various emissions from the upper atmosphere that are point-like and bright enough to correct infrared images. Unfortunately, the atmosphere trembles in such a manner that using AO techniques to correct distortions in starlight becomes rapidly more difficult as one attempts to correct the shorter wavelength components of the starlight. It is now apparent that new guide stars with greatly increased brightness at visible wavelengths will be needed if visible images are to be corrected. It is the aim of this project to provide such guide stars as will enable AO correction of visible starlight. In this project we will also assess the possible contributions of enhanced remote optical sources to the measurement and detection of optical turbulence itself.

2. Status of Effort (9/15/01)

2.1 We established by experiment and theory that a 1/4 Joule, 30 nsc, violet laser pulse focused in the stratosphere, would exceed the threshold for producing a "super-bright" stimulated-Raman-backscattered pulse: the return would appear to be orders-of-magnitude brighter than the sun (at the earthbound transmitter of the violet pulse). In order for such pulses to probe the entire cylinder of atmosphere in which turbulence might affect a star's image in a large telescope, one would require: 1) over a half dozen different pulse focal points, and 2) over one hundred multiple pulses per second. This would require a total average laser power in the kilowatt range, more than was deemed acceptable (at present) by the night-sky astronomers we polled. Solar astronomers we polled were not interested because they have space vehicles orbiting the sun that obtain high resolution images.

Interest in our Raman-laser guide star would be forthcoming however if it could sense the "tip-tilt" noise from the telescope mount and zero-order turbulence, which, in the above form it can not. To this end we initiated research on various atmospheric effects that might be initiated by pulses that are very much shorter than the time between the collisions which give the Raman lines their linewidth, i.e., much shorter than 10^{-10}s at sea level for both O_2 and N_2 rotational S-band lines.

One effect, which we call "Raman line locking", seems especially worthy of further investigation. See Sec. 3.1. This effect, which we predicted and then demonstrated in ambient air, requires a femtosecond laser pulse (of practically any wavelength) whose energy exceeds a certain threshold value, which is near 30 microjoules at 800 nm in air. This effect should occur at a high-altitude focus of a stronger stimulating laser pulse where it would essentially down-shift the carrier frequency of the upward-travelling pulse. The frequency-shifted pulse might then excite any of various resonances in the stratosphere and mesosphere, having avoided being absorbed in the troposphere. Raman line locking is analogous to "mode-locking" of lasers, hence its name, as we describe in Sec. 3.1.

2.2 We completed our effort to establish the effect of shortening the laser-guide-star pulses on the degree to which the pulses' state of linear polarization could be established, and on the degree to which atmospherically-induced changes in this polarization state could be detected. We proved that Maxwell's equations place no limit on the degree to which finite-energy ultrashort laser pulses can experience extinction through real finite crossed polarizers. See Sec. 3.2.

2.3 We completed our theory and experiments on speeding the response of currently available photorefractive spatial-light-modulators. These are being used in adaptive-optics devices to correct image phase profiles. Our results (Sec. 3.3) suggest that any future efforts to improve photorefractive modulator speed would have to be considered of low probability of success.

3. Major Accomplishments (3/15/98 to 7/15/01)

3.1 When femtosecond near-infrared laser pulses with pulse energies greater than ten millijoules are propagated in ambient air, they self-focus into one or more bright, self-guided, light channels (A. Braun, et al, Opt. Lett. 20, p. 73 (1995)). These channels can persist for many kilometers (L. Woste. et al, Laser Optoelektron. 29, p. 51 (1997)), and produce intriguing phenomena such as initiating lightning. In this project, we predicted, and found experimentally, that femtosecond pulses, having orders-of-magnitude-lower-energy (>10μJ), will produce a remarkable but much different effect in ambient air that does not involve self-focusing, an effect we call "Raman line locking".

We predicted, and found experimentally, that a femtosecond laser pulse whose energy was 10^{-3} below threshold for self-focusing does reach threshold for stimulated Raman scattering (SRS) in ambient air: 30 microjoules in a 120 fs, 800 nm, pulse. This energy is also considerably lower than the value we calculated for the SRS threshold of the strongest Raman line of molecular nitrogen (N_2) (a calculation that we verified experimentally early in this project using 240 times longer pulses in air under 70 bar pressure). One reason for the very low threshold is that all N_2 and O_2 molecules, regardless of their rotational state, contribute coherently to the ~120 fs Raman-scattered pulse, as explained in Pub. 4.7. We call this new effect "Raman line locking" in analogy to "mode locking" in laser cavities, when each mode contributes coherently to the creation of an electric-field pulse. To observe Raman line locking we used a setup shown schematically in Fig. 3.1. Gaussian laser pulses of 1/e diameter 5 mm, pulse length 130 fs FWHM, carrier wavelength 789 nm, and adjustable energy are focused by a 20 cm focal length lens L1 into the ambient air. There is no measurable scattered light or sound from the focal region from which the pulses, without visible distortion, diverge normally. At 30 to 100 cm beyond L1, a small fraction of the beam is focused by a microscope objective lens L2 into a 100 μm diameter, 10 cm long, glass fiber conduit to a spectrometer. The distance from L1 to L2 was adjusted to keep the spectrometer response

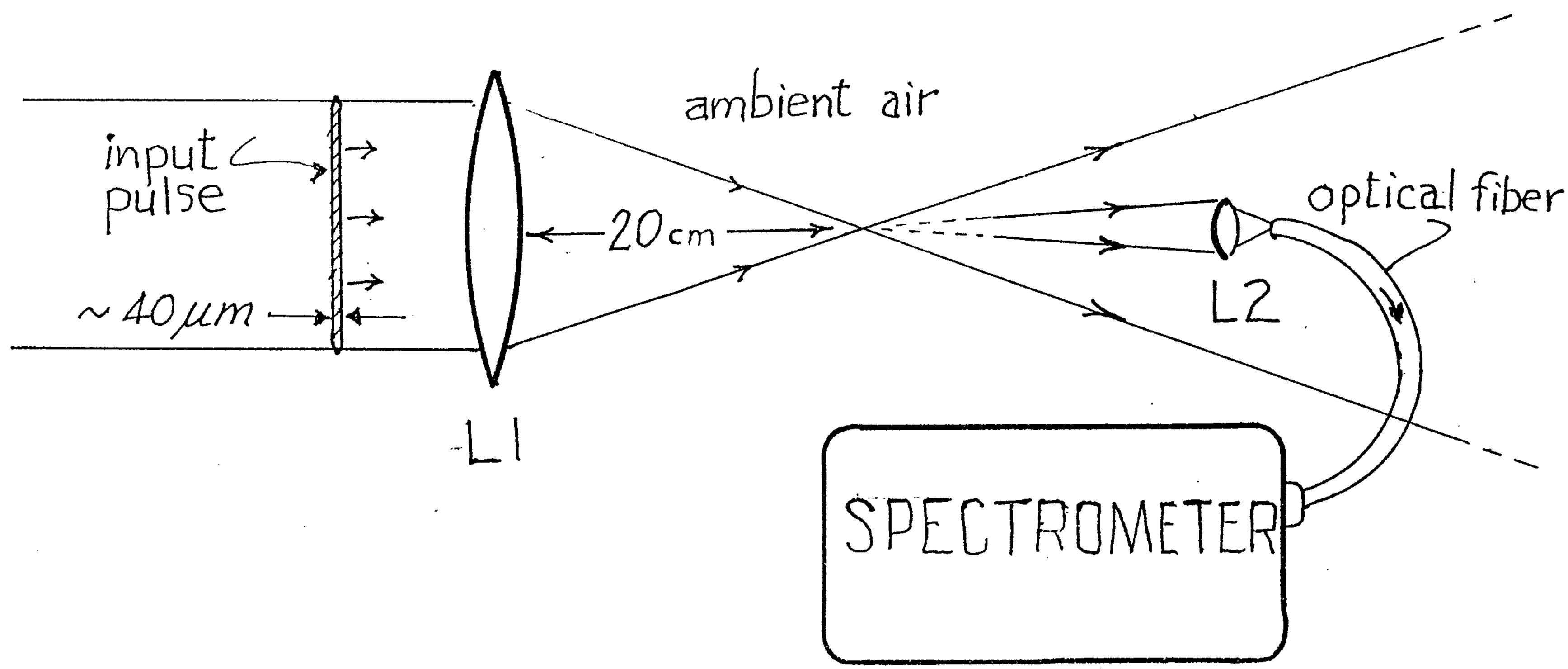

Fig. 3.1
Schematic of apparatus for recording spectra of focused femtosecond pulses.

linear. The spectra for pulses of energies 29, 64, 125, 273 and 577 μJ in a single data run are shown in curves Sp #3, 6, 5, 4 and 1, of Fig. 3.1, after the background Sp #2 has been subtracted.

For comparisons to the theory of Pub. 4.7, the most relevant spectra are Sp# 3 and Sp# 6 from the two lowest energy (29 and 64 μJ) focused pulses. These show mainly the shift of energy away from the input line-center to two broad lines whose centers are seen to be Stokes-shifted by 53 and 106 cm^{-1}. The 53 cm^{-1} Stokes line shift and its growth rate (~10^{-2} nepers per microjoule) are, within experimental error, what our numerical calculations predicted for a 120 fs transform-limited pulse whose envelope was of gaussian shape both transverse and parallel to the pulse velocity. (This agreement may well turn out to be somewhat fortuitous.) The doubly Stokes-shifted 106 cm^{-1} sideband grows similarly, not unlike what may be seen in ordinary single-line SRS experiments.

Spectra were also taken with the focusing lens removed at the beginning, in the middle, and at the end of the data run. They were indistinguishable and are displayed (renormalized for convenience) as Sp# 9 in Fig. 3.2. Unfortunately, after this data run a series of unrelated apparatus failures followed by the departure of two key personnel have prevented our obtaining additional data runs to clarify certain mysterious features in Fig. 3.2 that we comment on below. First we see the basic features predicted by our theory in the spectra Sp# 3 and 6 of the focused pulses having the lowest energies. At higher pulse energies, Fig. 3.2 shows less percentage growth in the fundamental 53 cm^{-1} Stokes sideband, and much more growth in the 106 cm^{-1} Stokes sideband, into which there is seen to be 10% conversion of a 577 μJ pulse. At the 0.1 to 0.6 mJ energies, deviations of the input spectrum Sp# 9 appear to be magnified. Also there is strong conversion to the anti-Stokes wings reminiscent of self-phase modulation spectra.

The conclusion from the experiments is clearly that a sub-millijoule, 120 femtosecond, gaussian laser pulse which is focused 20 cm into ambient air will emerge accompanied by one or more congruent gaussian pulses whose carrier frequencies are downshifted by multiples of a value (~53 cm^{-1}) that is roughly the Stokes shift of the centers of the rotational Raman S-bands of nitrogen and oxygen. The theory that predicted this, also predicts that the above statement will remain true for ever-longer focal distances than 20 cm, even up to tens of kilometers, in ambient air. This suggests that any subsequent research on Raman line locking might approach it as a means to generate a strong femtosecond pulse in the mesosphere whose carrier frequency is such that the pulse would have been absorbed by the atmosphere had it travelled there from earth; on the other hand, the "pump" pulse generated on the earth need not be absorbed on its journey up.

3.2 The standard gaussian-beam formulae for the electric and magnetic fields of a well-collimated, linearly polarized optical beam do not give accurate values for these fields in the "wings", i.e., beyond a certain distance from the beam axis. See Pub. 4.2. Because various atmospheric sensing schemes use beam-polarization fluctuations, we studied the limit to which exact solutions of Maxwell's equations in vacuum may have the fields in their wings have their transverse components match those near beam center, and thus perhaps experience non-zero extinction by crossed polarizers. The result surprised us: they can match perfectly; i.e., Maxwell places no limits on the degree of extinction achievable by crossed polarizers. Briefly, we found analytic expressions for collimated, finite-energy, electromagnetic pulses whose electric vector everywhere in space lay in the same plane. If the pulse direction was $\hat{z}$, then the exact electric-field

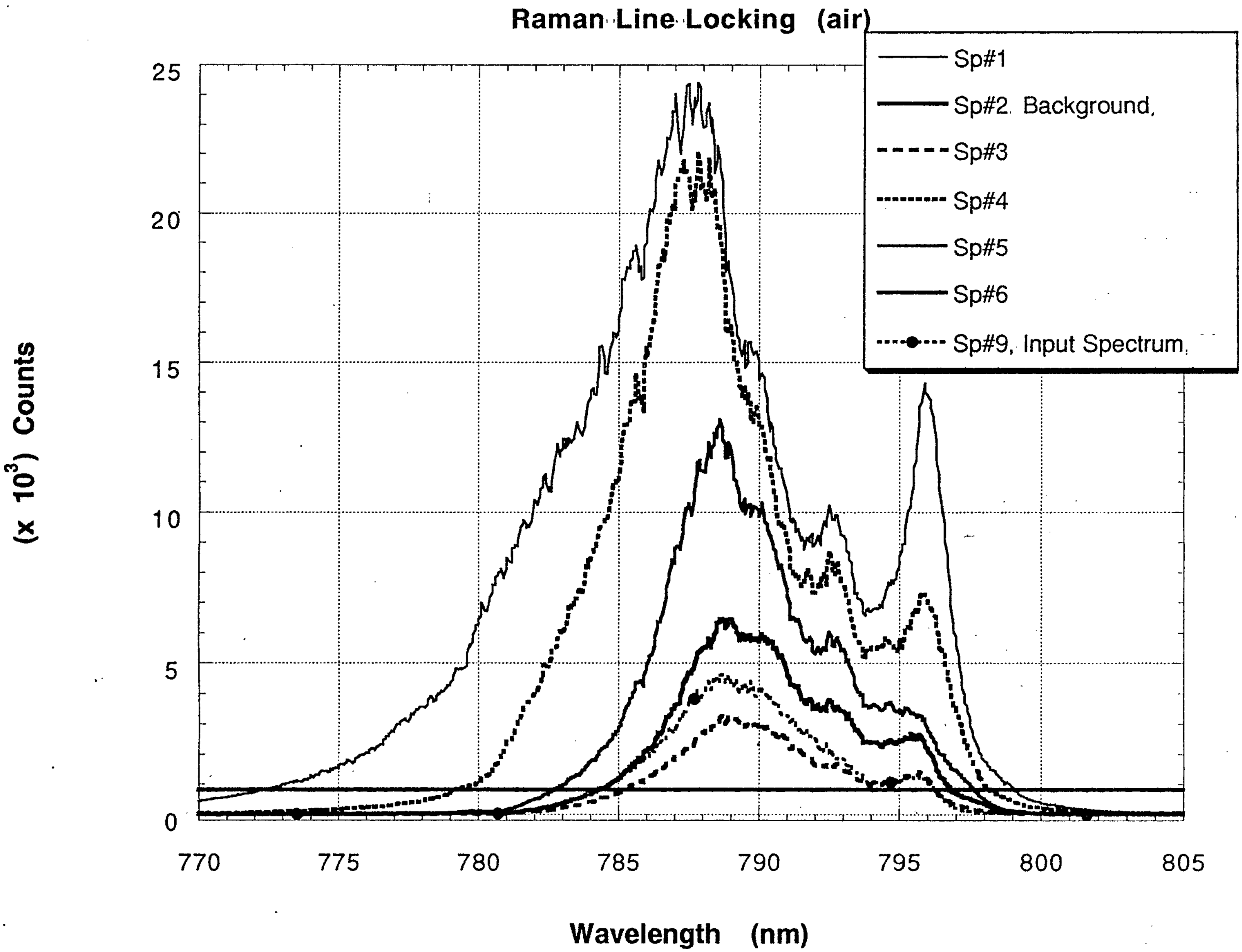

Fig. 3.2
Raman line locking spectra recorded with apparatus of Fig. 3.1. The input pulse energies in microjoules were as follows: (Sp# 1) 577 ; (Sp# 2) 0 ; (Sp# 3) 29 ; (Sp# 4) 273 ; (Sp# 5) 125 ; (Sp# 6) 64 ; (Sp# 9) superposed spectra of unfocused pulses of various energies recorded before, during, and after the previous spectra of focused pulses.

solutions had zero y-component everywhere, although the concomitant magnetic field had all (x, y and z) components nearly everywhere. The dual of this solution had, of course, a magnetic field whose y-component was zero everywhere. We were also surprised to find that our analytic expressions for the exact Maxwell solutions differed immeasurably (where the field amplitudes were above 10^{-3} of their maximum value at a particular z) from fields constructed from the solutions to the paraxial approximation (e.g., "gaussian" beams) provided that the beam divergence angle (FWHM) was less than 32 degrees (f-number greater than 2). Details of our analytic expressions are found in Pub. 4.4.

3.3 Adaptive optical (AO) systems for astronomy currently depend on "rubber mirrors" to impose phase corrections on incoming starlight. These mirrors employ electro-mechanical actuators behind a flexible reflecting membrane to obtain the large phase corrections (up to 8π) necessary. They are very expensive, of limited pixel number, and suffer from hysteresis. Liquid-crystal light modulators are as yet too slow and have difficulty getting phase corrections higher than 2π. Some non-astronomical adaptive optical systems use phase-correctors based on photo-refractive spatial light modulators. These can achieve 8π phase correction, reversibly and on many more pixels, but respond too slowly. The photo-refractive crystal of choice for these modulators is undoped n-type cubic $Bi_{12}SiO_{20}$ (n-BSO). In this project we completed theoretical and experimental studies on n-BSO and found that its speed-of-response is already intrinsic in the best crystals, and therefore cannot be improved. The limiting speed of response is proportional to the band mobility of photo-excited electrons in the conduction band. First, we found that the band mobility was the same in three carefully-grown crystals from three sources. This suggested that their mobilities were of an intrinsic nature. Then we adapted existing electron-phonon scattering theory to incorporate all nine of the prominent polar-phonon branches of n-BSO. We found excellent agreement between this theory and temperature dependence of the mobility using one adjustable parameter: the effective mass of an electron in the conduction band, which has not yet been determined by independent means. Therefore, we feel justified in concluding that any further efforts to improve photo-refractive spatial light modulators must be examined closely for probability of success for the given cost.

4. Publications

4.1) "Stimulated Raman backscattering from the stratosphere: a useful guide star for blue starlight?", R.W. Hellwarth in Proceedings Nr. 55, Edited by N. Hubin (Published by the European Southern Observatory, Garching, Germany, 1998): pp. 192-197.

4.2) "Guoy shift and temporal reshaping of focused single-cycle electromagnetic pulses", Simin Feng, H.G. Winful, and R.W. Hellwarth. Optics Letters. Vol. 23: pp. 385-387. March 1998.

4.3) "Stimulated backscattering from the stratosphere: a useful guide star?", R.W. Hellwarth, J.P. Partanen, and Nansheng Tang in Conference on Lasers and Electro-Optics, OSA Technical Digest (Optical Society of America, Washington DC, 1999), p.95.

4.4) "Spatiotemporal evolution of focused single-cycle electromagnetic pulses", S. Feng, H. Winful, and R.W. Hellwarth. Phys. Rev. E Vol. 59: pp. 4630-4649, April 1999.

4.5) "Mobility of an electron in a multimode polar lattice", R.W. Hellwarth and I. Biaggio. Phys. Rev. B, Vol. 60: pp. 299-307, July 1999.

4.6) "Nonlinear optical spectra of C70", F. Strohkendl, T. Axenson, R. Larsen, L. Dalton, R. Hellwarth, and Z. Kafafi, Chem. Phys. Vol. 245: pp. 285-295 (1999).

4.7) "Raman line locking in air" R. W. Hellwarth, to be published in Phys. Rev. B.

5. Personnel Supported

Dr. R.W. Hellwarth

Dr. J. Partanen

Dr. N. Tang

Mr. Sunkwang Hong

6. Interactions

Consulting of P.I. at Lawrence Livermore National Laboratory on Lasers.

7. Inventions and Patents

None

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EDUCATION: B.S. in Electrical Engineering, Princeton University, 1952.
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EMPLOYMENT:

1970 - : University of Southern California. George Pfleger Professor of Electrical Engineering and Professor of Physics.

1955 - 70: Hughes Research Laboratories, Culver City - Malibu. 1955-62: Member of Technical Staff; 1962-67: Senior Staff Physicist;1967-70: Senior Scientist; 1968-70: Manager, Theoretical Studies Department.

1970 - 71: Clarendon Laboratory and St. Peter's College, Oxford University, Oxford, England. National Science Foundation Senior Postdoctoral Fellow.

1966 - 70: California Institute of Technology. 1966-69: Senior Research Fellow, Electrical Engineering Department; 1969-70: Research Associate, Electrical Engineering.

1964 - 65: University of Illinois, Urbana-Champaign.Visiting Associate Professor in Electrical Engineering and Physics.

1955 - 63: California Institute of Technology. 1955-56: Hughes Postdoctoral Fellow; 1956-63: Visiting Lecturer.

HONORS: Rhodes Scholarship (1952), L.A. Hyland Patent Award (1965), National Academy of Engineering (1977), Charles Hard Townes Award of the Optical Society of America (1983), Quantum Electronics Award of the IEEE (1985), National Academy of Sciences (1986).

PATENTS: Giant-pulse (Q-switched) laser, nonlinear optical microscope, optical phase conjugators employing nonlinear refraction.

PROFESSIONAL ACTIVITIES: Fellow: American Physical Society; IEEE; American Association for the Advancement of Science; Optical Society of America; Member: American Association of University Professors; RESA Sigma Xi; Outstanding Educators of America; DOE committee on Inertial Confinement Research Policy (1975-76); National Materials Advisory Board -- NAS ad hoc committee on high-power laser-window materials (1971-72); and organizing committees for national and international scientific conferences: Associate Editor, IEEE Journal of Quantum Electronics (1964-76); Editorial board of Quantum Optics journal (1988-92).

8. Honors/Awards

See attached Curriculum Vitae.